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Psychology

Depth, motion, and static-flow perception at metaisoluminant color contrast

(color psychophysics/isoluminance/polarity reversal)

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ABSTRACT **Many experiments concerned with the role of color in depth and motion perception have applied isoluminant random-dot stereograms and cinematograms. The poor performance in the absence of luminance contrast has been associated with color-blindness of stereopsis and motion perception [Livingstone, M. S. & Hubel, D. H. (1987) *J. Neurosci.* 7, 3416–3468]. Nevertheless, isoluminant stimuli are not fully accepted as appropriate tools in isolating central mechanisms [Logothetis, N. K., Schiller, P. H., Charles, E. R. & Hurlbert, A. C. (1990) *Science* 247, 214–217]. In our experiments we use a broad luminance range to test whether color can contribute to a given mechanism when luminance contrast is present but has a strong "veto" effect from opposite luminance contrast, a condition we named "metaisoluminance." There is no fusion in stereopsis under polarity reversal, when only luminance information is given, and reversed-phi phenomenon is experienced for motion. As a third "matching" task, we included polarity-reversed random-dot Glass-patterns, which exhibit "static flow" and also show pattern reversal. We found that color can counteract the effects of polarity reversal by restoring stereoscopic fusion and reversed phi motion and does it with increased efficiency as the hue contrast increases. We found no such effect of color in Glass-patterns. Thus, we showed that the visual system for binocular depth and motion perception is not color-blind, although correlated hue information under metaisoluminance does not appear to yield shape perception.**

At the time R. L. Gregory asked the question "What does happen to perception when there is colour contrast with no brightness contrast?" (1), he probably did not think that the answer 10 years later would rather be the dilemma: "does anything (except consensus between investigators) actually disappear at isoluminance?" (2). It started with the interpretation of the findings by Lu and Fender (3), followed by Gregory (1), who reported a total loss of global stereopsis of random-dot stereograms (RDS) and a great loss of stereopsis of classical line stereograms at isoluminance. Of course, at isoluminance, a most unnatural situation, anything can happen, from loss of figure-ground segmentation to loss of depth; however, to conclude from that alone that the stereopsis mechanism is color-blind is very speculative. What is more curious is the fact that, years before isoluminance experiments, some robust evidence existed that stereopsis must utilize color information. Indeed, Julesz (4, 5) demonstrated that the two-gray-level polarity-reversed random-dot stereograms (PR-RDS, see Fig. 1 *Upper*) cannot be fused; but if in place of the two gray levels two similar colors are used in the left and right PR-RDS, respectively (Fig. 1 *Lower*), then fusion can be restored (ref. 6, pp. 76–77). This homochromatic presentation can restore fusion, as if the corresponding colors would counteract the strong binocular rivalry due to the opposite luminance contour gradients. An earlier experiment using polarity-reversed classical (line) stereograms with homochromatic colors was reported by Treisman (7). However, since black and white polarity-reversed classical stereograms can be fused (8), this experiment does not prove that stereopsis cannot be color-blind.

That stereopsis utilizes color is also suggested by the work of Greenberg and Williams (9). They bleached the red and green receptors with a bright yellow light and showed that dim violet RDS still yielded correct depth percepts. "With the additional assumption that signals from the blue-sensitive mechanism do not contribute to luminance, these results confirm that purely chromatic signals have access to stereoscopic mechanisms" (9). In this assumption the prominent idea is that, if the blue mechanism does not contribute to luminance, then depth can be processed by the visual system based on color alone.

If we regard the color PR-RDS and PR-RDC (polarity-reversed random-dot cinematogram) as a condition of "metaisoluminance," we can show that the correlated color information can still be utilized by stereopsis and by the motion system to yield depth and movement that is detached from shape. Indeed, at isoluminance many neural analyzers may still get some correlated luminance information because of some chance fluctuations. Under contrast reversal between a left and right stereo pair or between successive monocular arrays in time, there is no correlated luminance information. However, correlated color information yields a perceivable depth or veridical motion percept of the colored random dots; furthermore, we note that these dots do not form into a cyclopean coherent shape hovering in depth or a solid square moving in the midst of dynamic noise. Although in the present article we only study in detail depth, motion, and "static flow" in Glass-patterns conveyed by color under polarity reversal, the lack of shape perception is such a prominent fact that ignoring this observation would give a rather false impression of our findings. The perceived depth and motion of dynamic noise appears as the Gestaltist's "common fate" where, say, red and white dots independently share similar depth or motion direction but perceptually are not grouped together. A better word for "grouping" might be the complete lack of "coalescing or adhering" into a unified shape (form). In a sense, we were able to experience depth and motion as a pure percept without being attached to the surface of an object.

Our experimental contributions here are 3-fold. (*i*) We repeated the original homochromatic PR-RDS experiment of Julesz (6) with the most recent image-displaying techniques and controls. (*ii*) We extended the concept of homochromatic polarity reversal to RDC (PR-RDC). Specifically, we explore whether color can counteract reversed-phi motion, discov-

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Abbreviations: RDS, random-dot stereogram(s); RDC, random-dot cinematogram(s); RDG, random-dot Glass-patterns; PR-RDS, PR-RDC, and PR-RDG, polarity reversed RDS, RDC, and RDG.

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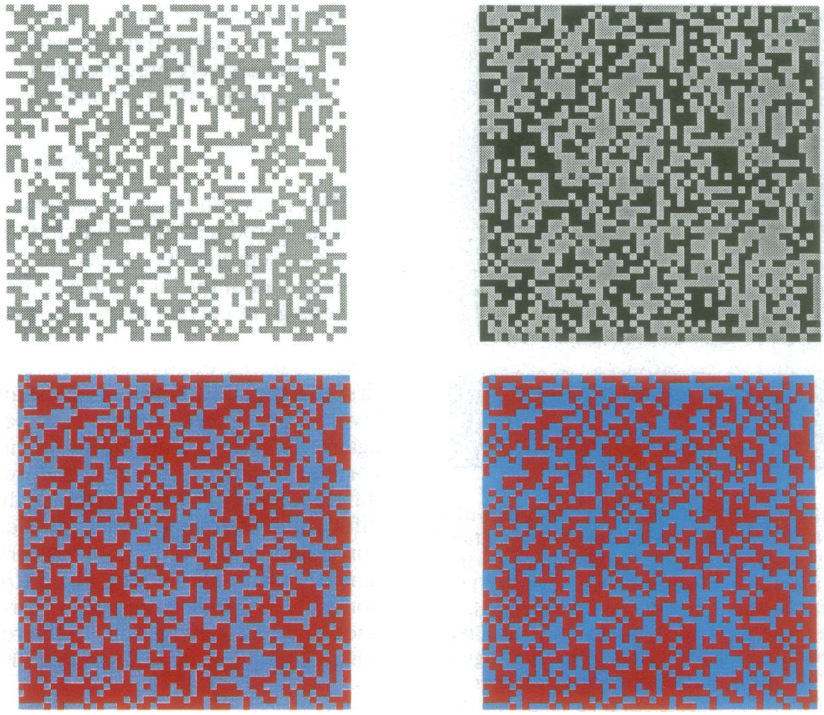

FIG. 1. (*Upper*) Achromatic PR-RDS. Complete negative correlation gives rise to binocular rivalry, and stereopsis can never be obtained. Notice that *Left* and *Right* are not photographic negatives of each other, the "background" is the same gray level in both images, and the "dot" coloring is changed from black to white. (Although the patterns are 50%-density random-dot patterns, in this study we refer to those corresponding dots that have the same luminance in a pair of RDS, RDC, or RDG as the "background," and we call the corresponding points with mismatched luminance level as "dots.") (*Lower*) Colored PR (metaisoluminant)-RDS with crossed disparity. The intensities of the two gray levels should be the same as in the *Upper* one. The central square can be seen in depth, although the borders are not clear, and the dots do not seem to be "coalescing" into shape. (The illustration is merely for didactic purposes and cannot be printed in the quality necessary for demonstration.) [Stereograms used in the experiments were generated on a Silicon-Graphics (4D/35, Mountain View, CA) IRIS personal computer and displayed on a stereo-ready Mitsubishi HL6915K color monitor, allowing 1270 × 1040 addressable pixels, with γ-correction. For the stereoscopic displays, liquid-crystal eyewear (Crystal Eyes, CE-1, Stereo Graphics, San Rafael, CA) served to separate the views of the two eyes as they were displayed on the monitor alternating at 120 fields per sec. To play safe, for all measurements a Kodak Wratten gelatin filter (no. 21) was used, which rejects all wavelengths below 540 nm, thus disabling the short-wavelength cones.]

ered by Anstis and Rodgers (10, 11). In addition, we included homochromatic polarity-reversed random-dot Glass-patterns (PR-RDG, see Fig. 2) in our studies, since according to Prazdny (12) gray polarity-reversed Glass-patterns cannot be seen. (*iii*) Encouraged by the experimental results, we propose the following general question: "What happens to vision when, besides color, luminance contrast is also present, but in such a way that it has a clear inhibitory effect?" That is, "can color feed into the visual system in the presence of a strong 'veto' from reversed luminance polarity?" If it does, then the system must utilize color.

METHODS

The rationale was a reversed-polarity paradigm with hue similarity. To avoid the unsolved problems arising from the lack of a real metric of comparing color and luminance contrasts in strength and from the fact that stimuli that were designed in isoluminance might have some residual luminance component, we have developed an experimental paradigm based on mapping the entire luminance-contrast range. This range contains: (*i*) correlated luminance polarities, (*ii*) isoluminance points, and (*iii*) reversed polarities. For RDS, RDC, and RDG, we used two different intensity levels of the same color for the first and second sets of dots, which could appear in the left and right eye image for stereo (Fig. 3); in the first and second frame of the apparent motion paradigm; or in a pair of the Glass-patterns. The two dot-luminance levels were kept constant (either at ±25% or at ±15% of the mean luminance, which was 32 candelas (cd/m^2) throughout all sessions, while the luminance of the background varied within a ±50% range from the mean luminance of the dots. In this way, it is ensured that both isoluminant and meta-isoluminant (i.e., reversed polarity) conditions are reached at given background luminances, and robust differences from the luminance-predicted curves (Fig. 4) in simple discrimination tasks will show pure color effects. According to our expectations, as shown in Fig. 4, in the case of achromatic presentation for RDS, RDC, and RDG, chance-level performance is expected when the background is roughly equal in luminance to one of the two dot luminances. In the opposite polarity range, either chance-level (stereopsis) or reversed (motion, Glass-patterns) performance is expected. If the minimum and/or the slope of the curve is changed with the addition of chromatic matching, we take it as a sign of utilizing color information. As the asymptote moves up to 75% correct in the reversed range, this is taken to reflect significant color contribution. To test the effect of distance in color-space of the contributing colors, we combined white or green "background" and white or red "dot" colors. Once a given chromatic contrast gives stronger input to the detectors at some neural level than the anticorrelated luminance input, the psychometric curve will not go down/reach/cross the 50% correct level, as shown in Fig. 4 *Upper*.

For all three subtasks, a two-alternative forced-choice discrimination paradigm was used. The subjects' task was to decide (*i*) whether the stereoscopically presented central square was in front of or behind the plane of the screen; (*ii*) whether the direction of coherent motion of random dots was to the right or to the left; or (*iii*) whether the global orientation of Glass-patterns was horizontal or vertical. We registered

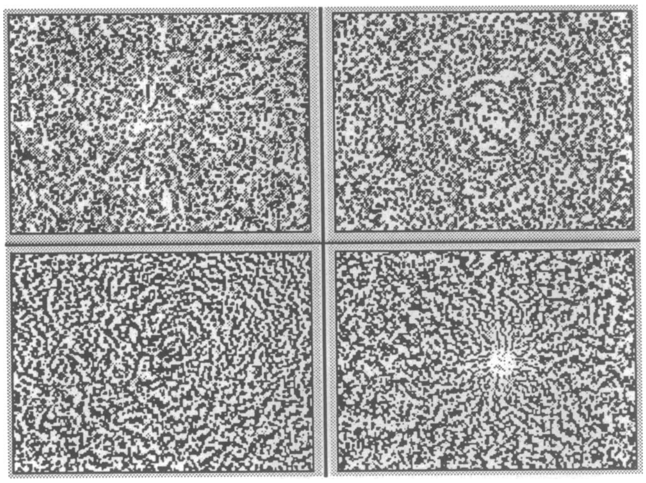

FIG. 2. (*Upper*) Two images of achromatic Glass-patterns without polarity reversal. It is easy to identify the radial transformation in *Left* and the circular transformation in *Right*, although the corresponding dots have different luminance levels. (*Lower*) The veridical transformations are the same, but the corresponding dots have opposite polarities. We found that under polarity reversal, if the global transformation is radial expansion (*Left*), observers give "circular" responses, and when the transformation is circular, a radial pattern is observed (*Right*). The same reversal holds for the simple translational patterns used in the experiments, that is, horizontal translation was perceived as vertical and vice versa. Color cannot turn back the orthogonally perceived patterns.

the percentage of correct responses. Each block consisted of 50 trials of a RDS, RDC, or RDG task. The background and dot luminance/colors were kept constant in one block. These blocks were repeated as up-down and as down-up parts of the varying background luminance sequences, giving 100 trials for every data point. Before each session, a 4-min color-adaptation stimulus of the appropriate random dots was given for the subjects. As subjects pressed one of the two response buttons, the next stimulus was presented with 120-msec delay. Stimuli were preceded and followed by a blank field of the background white luminance.

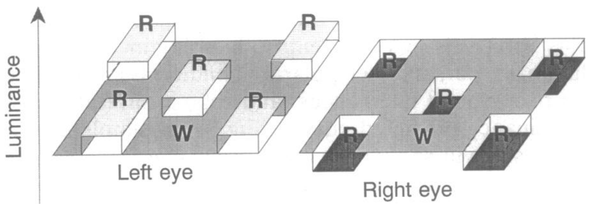

FIG. 3. Illustration of our reversed-polarity condition. In this example the background is white (W) and the dots are red (R) of different luminances in the RDS. In the experiments, the visual angle of all random-dot patterns was subtended 11 degrees both horizontally and vertically, and dot size was 4 min of arc diameter. Stereograms were 50% random-dot patterns, 90 × 90 dot, having a 60 × 60 dot central square at 8 min arc of crossed or uncrossed binocular disparity. Motion stimuli were random cinematograms of 50% density with a horizontal displacement of 8 min of arc. Glass-patterns were created by using a field of random dots with the above parameters, translating them horizontally or vertically with 8 min of arc spacing, and superimposing the translated version on the original pattern. Duration of RDS and RDG targets was 96 msec, whereas RDC targets were presented for only two frames (48 msec for each of them) with no interval between the two. In the chromatic experiments we used the maximum color separation between red and green guns of the monitor, these being our primary colors. To ensure the comparability of the chromatic and pure luminance tasks, red and green isoluminant points were determined with equal-energy white of 32 cd/m^2 (mean background luminance, measured on the screen without the stereoglasses and blue-rejection filter), and with ±25% and ±15% white dot luminances. (The heterochromatic flicker procedure was carried out with the appropriate random-dot patterns.) Our method is so robust, that the limitations of heterochromatic flicker do not interfere with the results.

RESULTS

RDS. Both conditions of luminance contrast (15% and 25% contrast) produced the predicted results for stereograms. In the reversed-polarity range there was no fusion that was independent of the luminance contrast. Fig. 5 *Left* shows the percentage of correct responses as a function of background luminance for the two dot-contrast settings in the achromatic case. As background luminance reached the luminance of the first (darker) dot, performance sharply decreased to chance level, staying there during reversed polarity and going up again only after leaving the second isoluminance point. In the correlated polarity ranges, the relatively high brightness difference between the corresponding dots did not result in difficulties of fusion and depth decisions. The addition of correlated color contrast of red primary to the same luminance contrast of the dots (Fig. 5 *Right*) reduced the effect of complete negative luminance correlation and gave rise to good depth discrimination. In the reversed polarity range, in which all luminance tasks are at 50% performance, even the

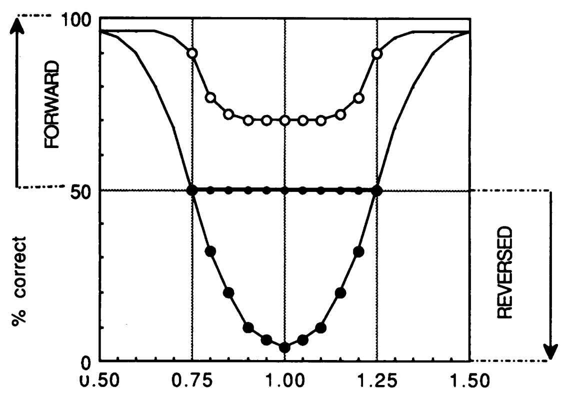

FIG. 4. Expected qualitative changes of performance in luminance-defined and color-and-luminance-defined depth (RDS), direction of motion (RDC), and direction of static flow tasks (RDG). The expected percentage of correct responses is shown as a function of background luminance for a fixed pair of dot contrast. The corresponding dot luminances in this example are at 0.75 and 1.25 background luminance units. The goal of the presented experiments was to obtain the middle part of the curve. If background luminance is between the two dot luminances, chance-level performance is predicted for stereograms with only luminance contrast (straight line with small filled circles at 50% chance-level performance). That means that there is no binocular fusion in the reversed-polarity range. For motion it is known that in the case of polarity reversal, motion detectors respond in the opposite direction of veridical displacement, and motion in the opposite direction is perceived (reversed phi phenomenon). In the reversed 0.75 to 1.25 range, a local minimum (near 0% forward response) shows that in the absence of a correlated luminance signal in the direction of displacement, there is still some nonambiguous luminance signal in the opposite direction (filled circles). We use the same prediction for Glass-patterns. Appropriate Glass-pattern presentation also results in reversed (orthogonal to the transformation) perception of static flow patterns (filled circles). The exact values of points on the curves are not of interest; we use the curves only to show the tendencies of luminance-defined perception. The "chromatic" curve shown by open circles indicates the condition in which the color of the dots is matched, even though their luminance polarity remains reversed. If color correlation contributes some input to a given process and it is stronger than complete negative luminance correlation, the chromatic curve should not cross the 50% chance level.

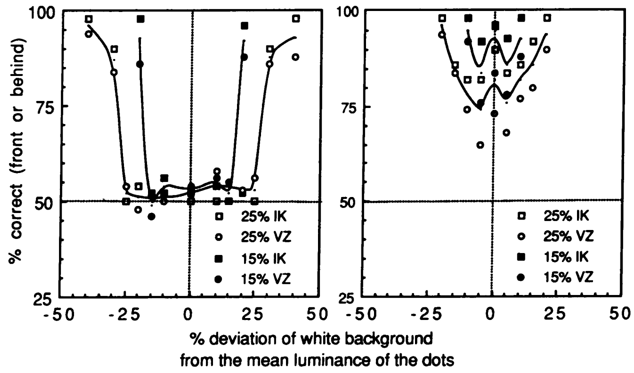

FIG. 5. Percentage of correct front–behind responses as a function of background luminance at 15% and 25% dot-luminance contrasts (two subjects, IK and VZ). The curves were drawn by interpolating between those points that were computed as average performances of the two observers. (*Left*) Achromatic RDS. Depth perception is impossible in the opposite polarity range. (*Right*) White-and-red RDS. Depth perception is restored by color correlation.

high-luminance-difference condition was around 80%, as plotted in Fig. 5 *Right*. (We found that fusion in PR-RDS is strong when the dominant eye receives the half image with higher average luminance; depth perception is more difficult, or in some cases impossible, when the bright image is shown to the nondominant eye. The explanation of this asymmetry is not clear yet, we show the results of the first case only.) We found that with red and green phosphors at our disposal, green primary could not override the effect of polarity reversal.

RDC. RDC performances in the achromatic case fit well to luminance predictions (Fig. 6). No matter how large the contrast difference was between dots in the two frames, reversed polarity always resulted in reversed phi. The ±25% contrast of the dots in the two frames could not be reversed by introducing red primary as the dot color (Fig. 6 *Right*). Direction of motion in the reversed-polarity range remained opposite to the displacement, and directionality could not be detected at isoluminant points. Decreasing the dot luminance contrast dramatically changed the effect of color. At ±15% contrast, reversed phi motion could be altered easily by color correlation, with forward motion being perceived. (We found a similar asymmetry, as with RDS. Forward motion was

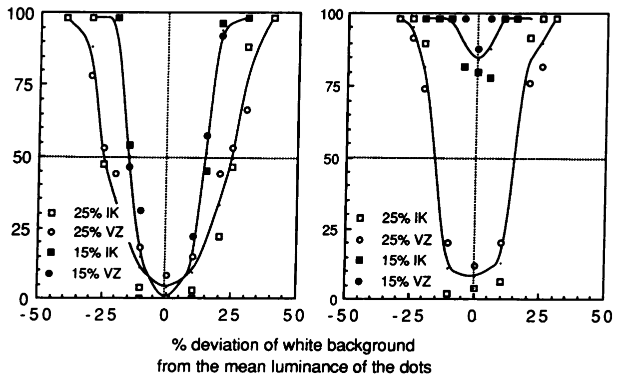

FIG. 6. Percentage of the correct forward direction of motion responses (same parameters as in Fig. 5; two subjects, IK and VZ). (*Left*) Achromatic RDC. Reversed polarity elicits completely reversed directional responses (0% correct forward performance means that the subject's responses are consistently in the opposite direction). (*Right*) White and red RDC. Since 25% luminance contrast cannot be affected by color, responses remain reversed. At 15% contrast, as a result of correlated colors, the forward phi phenomenon appears again.

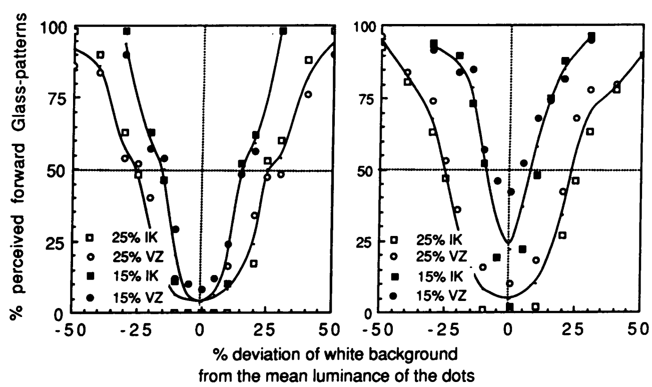

FIG. 7. Percentage of correct veridical static-flow responses (same parameters as in Fig. 5 *Right*; two subjects, IK and VZ). (*Left*) Achromatic RDG. Reversed polarity results in reversed directional responses. (*Right*) White-and-red RDG. The patterns appear unaffected by the chromatic input, even at low luminance contrast. In the reversed polarity range, orthogonal direction of flow dominates.

strong when the brighter frame is the first, whereas, when the temporal order was changed, reversed phi occurred again. Here, we show only those results that came from the bright–dark order.) As for RDS, green on white background could not override the effect of polarity reversal.

Random-Dot Glass-Patterns. Achromatic Glass-patterns with opposite polarity elicited reversed responses (Fig. 7 *Left*). In the chromatic condition, we found strong luminance-defined effects (Fig. 7 *Right*) with both curves (15% and 25% luminance contrast) having two crosspoints at the 50% performance level. At 15% contrast there was a slight shift towards the chance level, indicating some minor effect by the red.

Fig. 8 shows our results with red–green patterns. The difference between depth, motion, and static-flow performances is clear in this higher chromatic contrast condition. Note that luminance contrast is also high, ±25%, yet RDS are easily fused. RDC did not cross the chance level, and RDG still stayed reversed.

DISCUSSION

The problem of studying luminance and color variations in ways that are different from natural conditions opens up

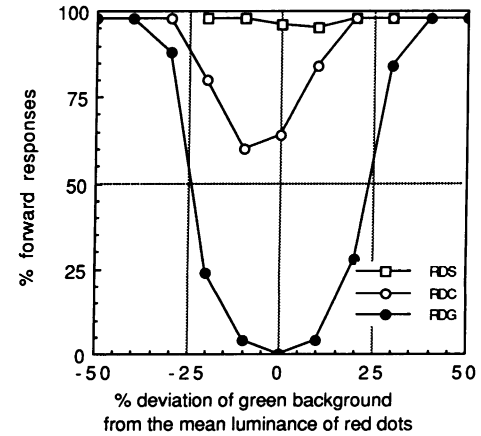

FIG. 8. Percentage of forward responses as a function of background luminance in RDS, RDC, and RDG tasks for one observer. Dot luminance is 25%, background color is green, dots are red. This higher chromatic contrast (as compared with the previous figures) strongly improves depth decision performances and ceases reversed direction of motion responses. There is no effect of color on Glass-patterns.

novel paradigms for psychobiology. Here we adopt the usage that luminance channels are also called "broad-band," and color channels are often referred to as "color-opponent." (We avoid the usage of the corresponding "magno" and "parvo" dichotomy because we are psychologists.) One of the more direct methods of addressing psychophysical questions of parallel pathways with different neurophysiological properties, such as color opponency and broad-band sensitivity, was the isolation of these systems by using isoluminant stimuli. Although the early experiments suggest that depth and motion processing is mediated only by the broad-band pathway, many recent experiments, even using the method of isoluminance, indicated that chromatic stimuli might be effective in both stereopsis and motion (13–18).

With the method presented here, where color is juxtaposed on complete negative luminance correlation, which we called metaisoluminance, we were able to avoid all artefactual luminance effects and to show that binocular depth perception and the perception of motion-direction is not color-blind. The effectiveness of color in opposing uncorrelated luminance signals is the function of chromatic contrast: a higher chromatic contrast can counteract a higher negative luminance contrast. We found that stereopsis has higher access to chromatic information than motion perception in the sense that color can restore binocular fusion in a larger luminance range of opposite polarity than it can overcome reversed-phi motion. This might be explained by supposing different levels of interaction between color and luminance pathways (19, 20). The gradual impact of color on different types of correlation processes (as seen in Fig. 8) shows that our specialized skills, like stereopsis and perception of motion- and static-flow, cannot be assigned solely to one of the retino-geniculate pathways. The classical observation that led to the conclusion that "Although some aspects of perception, such as movement perception or stereopsis, are completely lost or greatly diminished when borders consist of color contrast without luminance contrast, other aspects of perception, such as shape discrimination are only slightly degraded" (21) does not seem to be supported by the results obtained by our psychophysical method; as a matter of fact we found the opposite conclusion. In the light of our observation of "shapeless" depth in the case of metaisoluminant stereograms and our negative results with metaisoluminant Glass-patterns, we conclude that it is the perception of form and not the perception of depth or motion that is strongly damaged in the absence of consistent luminance cues.

Finally, we found some interesting unexpected results, such as a strong asymmetry for RDS depending on eye dominance and for RDC depending on precedence. Also, that green–white RDS and RDC behaved much worse from the, say, red–white case (see also ref. 22) raises questions about the green channel (although the limitation of green phosphor might be the culprit).

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